Enhancing Man-Portable Robot Functionality through Integration of New Sensor Payloads

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Abstract

The Technology Transfer project of the Unmanned Systems Branch at Space and Naval Warfare Systems Center, San Diego seeks to improve the functionality and autonomy of small mobile robot systems by harvesting prior and ongoing developments for insertion into current programs. Over the past year, we have been working with the Center for Commercialization of Advanced Technologies (CCAT) to integrate sensor packages from private companies to increase the payload options for small unmanned ground vehicles (UGVs). These sensor packages enable and enhance various aspects of robotic autonomy and human robot interaction. Combined with the Robotic Intelligence Kernel (RIK) software originally developed by Idaho National Laboratory, we have demonstrated and evaluated the commercialization potential of various capabilities on man-portable UGVs, such as radiation detection, simultaneous localization and mapping (SLAM), automatically deployed sensors for remote monitoring of previously explored areas, enhanced video, acoustic sensing, stereo vision, and advanced behaviors for human-robot teaming. These capabilities have been combined into modular payloads with standard interfaces, allowing for easy integration with a wide range of robotic platforms.

Keywords: robotics, architecture, payloads, sensors, navigation

1. Background

In late 2002, the DARPA Tactical Mobile Robot (TMR) program was transitioned to SSC San Diego to facilitate incorporation of the program's accomplishments into ongoing DoD developmental efforts. Initial successes led to the formal establishment of the Robotics Technology Transfer Project (TechXFR), funded by the OSD Joint Robotics Program (JRP), now the Joint Ground Robotics Enterprise (JGRE). The near-term objective was to increase the functionality and autonomy of man-portable robots, while simultaneously reducing the operator burden associated with teleoperated control. The TechXFR approach is to evaluate component technologies on prototype test platforms, fuse complimentary methods into an optimal solution, and then port results to fieldable platforms. Our principle focus was thus shifted from continuing development of more technology to expediting transition of usable R&D products to the warfighter. Our key collaboration partners include the Idaho National Laboratory (INL), the Jet Propulsion Laboratory (JPL), and SRI International.

1.1 Robotic Intelligence Kernel (RIK)

All component technologies described in this paper are integrated under an expanded version of a robot software architecture called the Robotic Intelligence Kernel (RIK)[1] , co-developed by INL and by SSC San Diego. To ensure cross-platform compatibility, the architecture is independent of the robot geometry and sensor suite, facilitating easy porting to any platform the warfighter might use. The RIK allows for expeditious development and integration of new payloads, perceptions, and behaviors by abstracting and publishing all data in a standard and easy to use manner. Finally, the architecture allows the robot to recognize what sensors are available at any given time and adjust its behaviors and perceptions accordingly. The RIK has been demonstrated across multiple robotic platforms including the iRobot PackBot,

iRobot ATRV Sr, iRobot ATRV Jr., ActivMedia Pioneer 2DX, Segway RMP, and SSC San Diego Robart III.
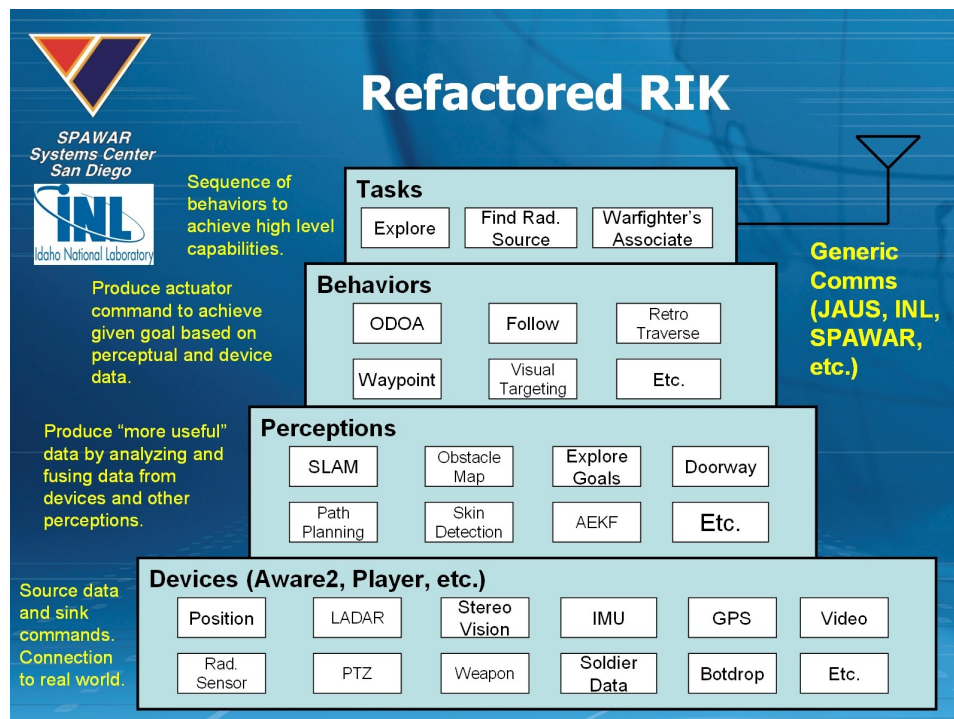

Figure 1 The RIK is a modular robotic intelligence software architecture which is capable of integrating advanced perceptive algorithms and behaviors on any platform because of its modularity and strong messaging backbone.

In order for TechXFR to integrate various component R&D technologies and evaluate different approaches to fusing sensor data and intelligent behaviors, a great emphasis has been placed on making robotic perceptions, behaviors, and tasks more modular. Figure 1 shows the modular nature of the RIK architecture, where the devices are sensors or payloads, perceptions are derived data based on device data, behaviors are robot actions determined by the perception and device data or user input, and tasks are strings of behaviors. The desired modularity has been achieved through standard data and command messaging between modules and use of a hierarchical state machine. The standard messaging makes it easy to add new modules, and the hierarchical state machine makes it easy to create new tasks, or strings of behaviors, which

provide new capabilities. The ability provided by the RIK to quickly and easily integrate new sensor payloads and to develop associated perceptions, behaviors, and tasks based around them greatly expedited integration of the CCAT payloads.

1.2 CCAT

To expand upon this promising concept, SSC San Diego has partnered with the Center for Commercialization of Advanced Technology (CCAT) to assist entrepreneurs in the transition of promising technology solutions. CCAT is a DoD-supported effort to help advanced technologies achieve success in the marketplace. The 2007 CCAT solicitation focused on proven solutions that could be quickly integrated onto field-ready man-portable robots, such as the Foster-Miller TALON and the iRobot PackBot. Managed by SSC San Diego, the CCAT program is administered out of two geographically dispersed offices, one in San Bernardino and the other in San Diego. The San Diego office, which operates out of the San Diego State University Research Foundation, follows a public-private partnership model. The San Bernardino office is a sponsored program managed and operated under the California State University San Bernardino Foundation's Office of Technology Transfer and Commercialization (OTTC).

During the summer of 2006, the CCAT program conducted a nationwide solicitation for near-term technologies that could improve the effectiveness of unmanned ground vehicles (UGVs) currently used in Afghanistan and Iraq. In October 2006, the CCAT office in San Diego announced business development grants and support awards to six companies, resulting in four successful transitions:

- iRobot - Navigator and Seer payloads providing visual odometry and the hardware to support SLAM algorithms on a PackBot.

- SpaceMicro, Inc. - RADSITE providing the ability to geometrically locate multiple radiation fields and influence the robot's search strategy

- CornerTurn - BotDrops providing persistent surveillance of a previously cleared facility or area

- SAIC - Birddog providing robot control without an OCU.

The TechTXFR project worked with each of the companies to integrate their technologies for evaluation and performance testing at SSC San Diego.

2. CCAT Payloads

Over the short span of 3 months, SSC San Diego received delivery of five payloads, which were rapidly integrated on different robotic platforms using the RIK software architecture. Once a driver was added for each payload or sensor, new behaviors and functionalities were developed for the RIK to maximize the capabilities of the payloads.

2.1 Navigator

Developed by iRobot Corporation of Burlington, MA and SSC San Diego and manufactured by iRobot, the semi-rugged Navigator payload for a PackBot Scout includes a Sick-LD OEM ladar, an Ublox GPS, a 3DM-GX1 IMU, a KVH gyro, a serial radio, and a processor with the computational ability to run the RIK on a man-portable robot. The Navigator payload came pre-installed with iRobot's Aware2 Beta software, which provides a standard interface to the payload sensors and the PackBot actuators. The initial integration of the Navigator payload required the ability to interface with Aware2. Once all the device drivers were added to the RIK via Aware2, porting the perceptual and behavior capabilities to the smaller platform was easily accomplished by tweaking configuration and co-variance values for each payload sensor, based on quantified sensor performance. The RIK and Navigator Payload

now allow the PackBot to be operated at varying levels of autonomy, whereas it was previously only teleoperated. All existing RIK functionalities are supported, including SRI International's simultaneous localization and mapping(SLAM) shown in figure 2 on INL's 3D interface[2], obstacle detection and avoidance (ODOA), seamless indoor/outdoor navigation, exploration, and communications support for multiple OCUs[3] and debugging tools.
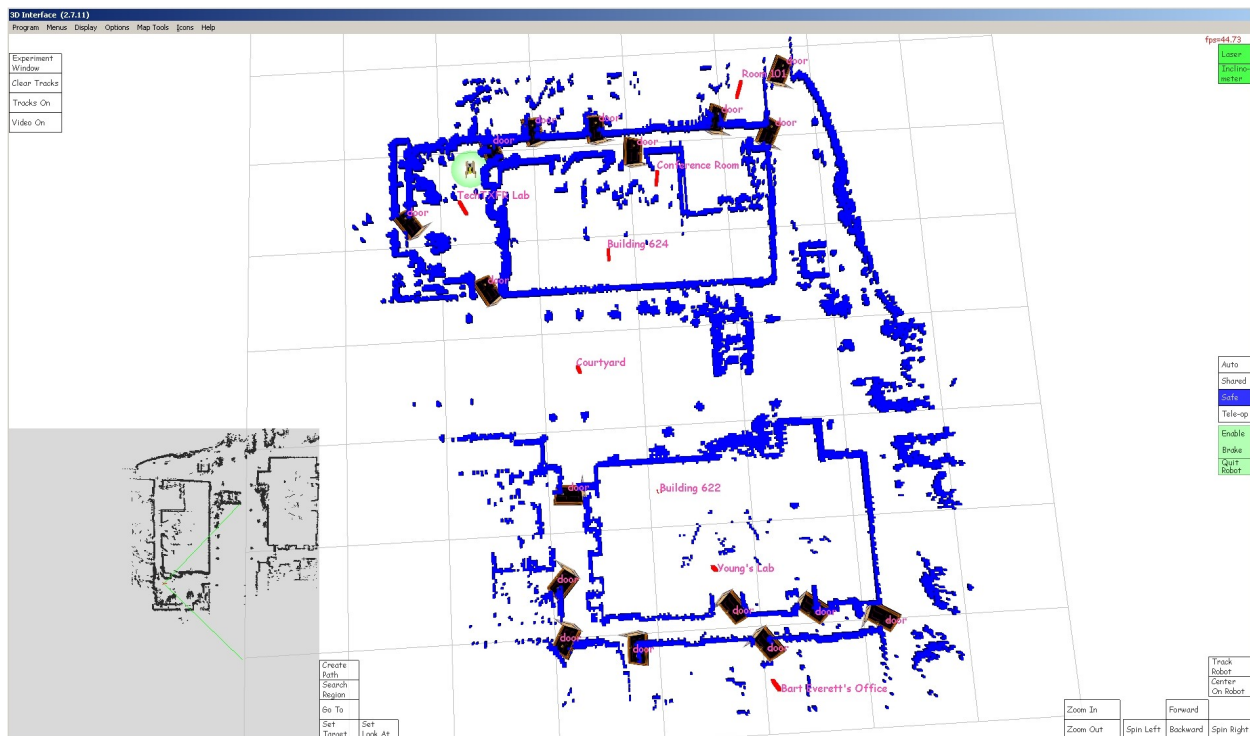

Figure 2 *A SLAM map of multiple buildings and outside courtyard at SSC San Diego made with the Navigator payload mounted on a PackBot. The map is displayed in INL's OCU.*

Even though all functionalities, intelligence, and communications were easily ported over to the PackBot, the navigation behaviors could only perform as well as the localization solution, which in turn is tightly coupled with the data coming from the odometry and navigation sensors. Most of the work to port the RIK and all associated behaviors to the PackBot, therefore, involved characterizing the Navigator payload sensors to find their strengths and weaknesses. To help

expedite this process, we expanded the RIK to provide tools for logging sensor data, parameter files for setting sensor co-variances, and configuration files for specifying which sensors to turn on and which perceptions and behaviors to run. For example, early implementations of the RIK only had a 180-degree scanning ladar used for various perceptions, such as SLAM and ODOA; the Navigator payload's 360-degree scanning ladar then introduced not only more data but also data corresponding to expanded coverage areas around the robot that we didn't have before. The RIK's sensor-agnostic ODOA instantly worked with this new sensor, but the configuration options for mapping on other platforms (e.g., an ATRV with a 180-degree SICK LMS ladar) didn't immediately work well with SLAM on the Navigator PackBot. This was due to multiple reasons, one being the need to accurately interpolate each individual point returned from the SICK LD as opposed to the whole scan with the SICK LMS. This difference is caused by the elapsed time between the beginning and end of a scan, due to the slower scan rate of the SICK LD, while trying to interpolate the data with respect to the robot's pose estimate, especially while the robot is turning

Because the tele-operated PackBots were not designed to perform precise servo-controlled movement, the stock odometry data provided, especially regarding the yaw angle, is not well suited for closed-loop autonomous navigation methods. Therefore, the navigational sensors on the Navigator payload were chosen to greatly enhance localization. The RIK feeds the sensor data into an Adaptive Extended Kalman Filter (AEKF)[4] developed under the TechTXFR project. The AEKF provides pose information that is orders of magnitude better than the raw odometry from the PackBot, allowing for more accurate navigation and control of the robot. The AEKF provides benefits over most common systems in two ways. First, it automatically adapts to the sensor and state noise covariances of the platform over time. This

reduces the need to manually tune the AEKF, which makes porting to different platforms much easier. Second, it also adapts the sensors that are being used at any given time to provide the best estimate of the robot's location state. For example, if the robot is outdoors in an open area, it might use GPS as a position estimate, but in GPS-denied urban environments, it would switch to using SLAM as the main position estimate. This particular feature provides the means for our PackBot to seamlessly transition indoors and outdoors during autonomous operation. Extensive testing on the Navigator PackBot has shown the relative position estimate provided by the AEKF to have an error of less than 1% of distance traveled, with the typical errors in the range of 0.6%, as shown in figure 3.
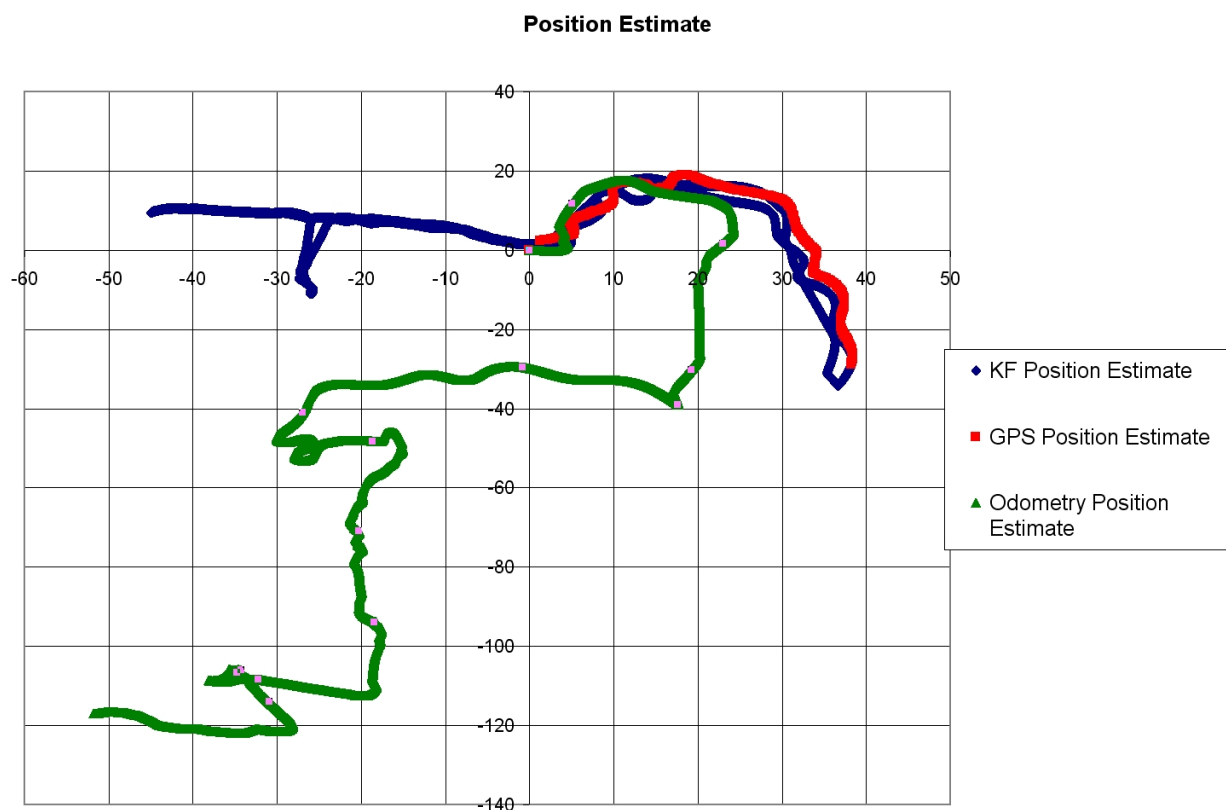
Position Estimate

Figure 3 Test results of the output of the AEKF(Blue) with the Navigator Payload versus GPS(red) alone and raw PackBot odometry alone (green) over a 323-meter outdoor and indoor course that included dirt roads and stacks of 2x4s. The relative error for the AEKF was 0.62%, which proved much better than raw odometry, which has infinite error, and GPS, which obviously fails indoors.

Current work is being done to optimize the RIK processes to increase the timing consistency and frequency of the AEKF thread to eliminate accumulated errors associated with larger step periods than those of our fastest sensor inputs. The goal is to get the error rates below 0.5% of the total distance traveled during each mission. The Navigator Payload (not including our software behaviors) is now available as an iRobot commercial product.

2.2 SEER

The Seer payload, also developed by iRobot, incorporates a Tyzx stereo camera head into a rugged enclosure that replaces the PackBot Scout head. 3D stereo data provides additional capabilities to the RIK, including 3D obstacle avoidance, visual odometry, and 3D modeling. Data from the payload is acquired through an Aware 2 interface in the form of a 3D point cloud. Once a raw point cloud has been obtained, a number of processing stages occur before the robot uses the data during its reactive and deliberative decision-making process. First the point cloud is cropped in 3 dimensions so that regions of the cloud that are not relevant to obstacle avoidance are ignored. For example, cropped regions include areas that are above the height of the robot, allowing the robot to navigate under tables, chairs, etc.

Next, the point cloud is projected into a world coordinate system, then projected onto a 2D obstacle map adapted from one developed by another project at SSC San Diego for unmanned surface vessel obstacle avoidance[5]. The obstacle map is probabilistic, allowing for the estimated likelihood of an obstacle to be determined by factors such as the number of times it has been detected by a sensor and the number of different sensors or sensor modalities that have detected it. The probabilistic framework also allows for some 3D data to be preserved during the 3D-to-2D projection stage. The 3D data is preserved through a function that correlates point cloud density to object probability (i.e. the more dense the stereo point cloud is in a region, the

more likely that the region contains an obstacle). A linear function is currently used for this correlation, with constants set through empirical testing.

The 2D obstacle map exists in a global coordinate system, and is persistent, in that object representations remain in the map even after the robot has passed by the objects and they have moved out of the field-of-view of the sensors. This persistence allows for better deliberative path-planning and can reduce the requirements for sensors covering all regions around the robot. Deliberative path planning is improved in cases where a user directs the robot back through previously navigated regions. A deliberative path can be planned around obstacles that have already been detected but are not currently in view, thus reducing the need for re-planning of paths as these obstacles reappear. Persistent obstacle maps can also reduce sensor coverage requirements. Objects detected in the sensor-rich forward path of a robot are still avoided even if they are no longer in view at a later time. For example, a robot with no rear-facing sensor will still be able to avoid backing into objects as long as these objects were first sensed by the robot as it passed.

There are future plans for the stereo data to be fused with data from laser and other sensors as part of the same obstacle map. Full 3D data can also be stored for rendering 3D models of the explored area as a post-processing step. We have already rendered models that fuse the stereo point clouds using the robot's Kalman filter to register scans. While this method is efficient because it doesn't require 3D correlation techniques, it subjects the resulting map to errors in robot localization.

2.3 RADSITE

The Domestic Security Division of Space Micro, Inc., now SD Technologies, developed the Radiological Source Identifier and Tracking (RADSITE™) technology. RADSITE (figure 4)

is designed to detect and geometrically locate multiple radiation fields in less than 1 minute, allowing the radiation sensor to influence the area search strategy, leading the robot directly to the source[6].

Figure 4 The RADSITE sensor, developed by SpaceMicro Inc., mounted on an iRobot ATRV Sr. The sensor provides azimuth and distance to radiation sources, allowing the robot to intelligently home in on its target.

RADSITE identifies the radiation source and provides an estimated location in the form of azimuth and range. Since the payload provides two possible bearings to the source due to symmetry in the sensors, the robot takes multiple readings from different locations to disambiguate the angles and obtain a valid bearing to the radiation source.

The plug-and-play nature of the RIK provided for fast integration of the RADSITE sensor, which required the development of new behaviors to enable the robot to use the heading data and drive towards the source. These behaviors were easily added to the RIK, since they were based on previously developed RIK behaviors such as GOTO, TURNTO, and WAIT. Combining these behaviors with the readings from the RADSITE sensor allows the robot to find an azimuth to the source after two readings and an estimated distance to the source after a third reading.

The next generation of the RADSITE sensor, to be completed in 2008, will be able to locate the source azimuth without ambiguity, eliminating the need for robotic disambiguation behaviors. This will allow the robot to locate the source more quickly. The new sensor will also be smaller and more rugged, allowing it to be used as a payload on existing man-portable robotic platforms.

2.4 BotDrops

CornerTurn, LLC, of Corona, CA, developed the BotDrops leave-behind sensors. The goal of this project was to demonstrate robotically deployed sensors that allow persistent remote surveillance of a previously cleared facility or area. The BotDrops include PIR and vibration sensors in a small brick-like enclosure that works with an existing deployer module developed in-house at SSC San Diego[7]. The deployer was already designed to fit on a PackBot and thus served as a quick feasibility demonstration of CornerTurn's leave-behind sensor concept. The BotDrops sensors also include wireless mesh networking radios for communicating between the sensors and an optional 802.11 or SatCom link node that can transmit data back to the user.

Adding BotDrops to a man-portable robot that has autonomous mapping capabilities will allow the system to enter a building, create a floor plan, and leave the sensor bricks at optimal areas of interest, such as hallway intersections and entrances/exits. This will allow the monitoring of a building once it has been secured. The BotDrops are deployed from the robot by command from the user, and the icon of where the sensor is placed is displayed in the map on the OCU. The user is notified when any of the BotDrops are triggered and the robot can autonomously return to that area for human presence detection and visual inspection.

2.5 Birddog

The Birddog human-robot-interaction concept, developed by SAIC of Englewood, CO, enables intelligent unmanned systems to reason about the actions and intentions of humans based on their location and weapon status. SAIC outfitted an M4A1 assault rifle, shown in figure 5, with an IMU, safety and trigger switches, and Bluetooth communications for sharing the weapon status. These sensors communicate with a PDA device worn by the warfighter. The PDA then transmits to the robot the status of the weapon, the direction it is being pointed, and the GPS location of the warfighter. Using this data, the robot can perform different behaviors in response to perceived actions of the warfighter, as first outlined in the Warfighter's Associate concept[8] .
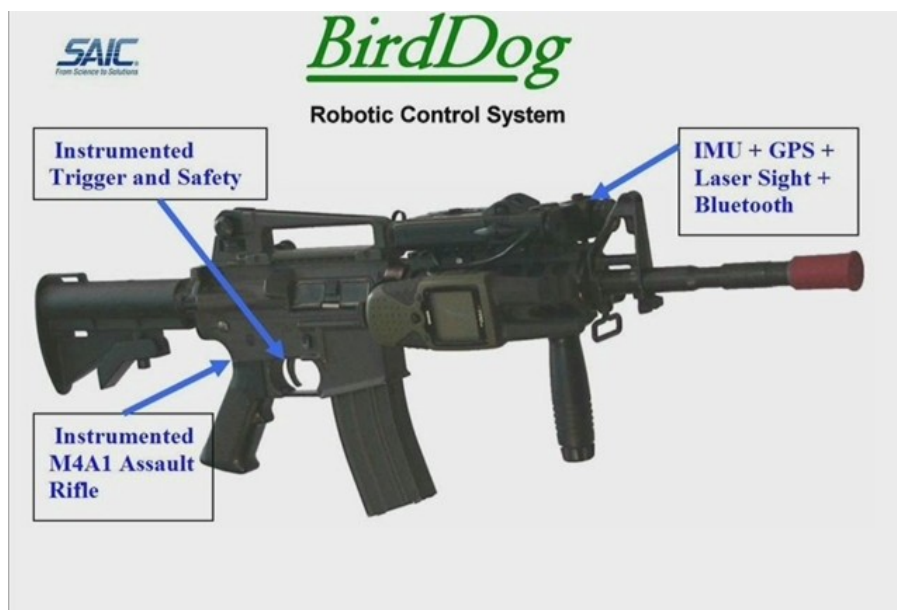

Figure 5 Diagram of the Birddog Warfighter Sensor System developed by SAIC of Englewood, CO. The system combines an instrumented M4 and PDA with GPS (not shown) to provide the robot data used to assess the situation and decide what its appropriate behavior should be.

Initially, a ladar and vision-based following algorithm is used to follow the warfighter into the tactical area. If the warfighter feels threatened and releases the safety on his or her

weapon, the robot will switch into a ladar-only following behavior while the pan-tilt unit, which can hold a camera and/or a weapon, tracks the azimuth and elevation movements of the rifle. When the warfighter opens fire, the robot uses the tracking location and the direction the weapon is pointing to provide cover by automatically placing itself between the warfighter and the perceived threat. As long as the warfighter is involved in the engagement, the robot will attempt to find and track adversaries using a sophisticated thermal processing perception and target tracking behavior. This could be used to help safely locate targets and verify that they are indeed hostile. Finally, if the safety on the warfighter's weapon is returned to the safe position, the robot will wait for the user to return to their last known location, at which point the mission is continued.

The initial "Warfighter's Associate/Birddog" implementation has received high interest due to the perceived usefulness of such a system in a combat situation. Having a robot available to carry gear, provide moving cover or possible suppressing fire, and also map unknown areas without adding complicated methods of control will be a useful tool to the warfighter.

3.0 Summary

SSC San Diego's effort to team with CCAT proved to be a fruitful endeavor for all parties involved. The individual companies were able to demonstrate their prototype payloads on an autonomous robot while SSC San Diego was able to evaluate a range of payloads that could provide new capabilities for man-portable platforms in the near future. The RIK proved to be a modular architecture that facilitated rapid integration of new sensors and development of new behaviors. Further work with CCAT on their 2008 awards is already in progress with expectation of continued success.

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